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Search for double β -decays of ^{124}Xe with XENON100 & XENON1T

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Abstract. The rare nuclear process of two-neutrino double electron capture, where two electrons are simultaneously captured from the atomic shell, has not yet been observed for ^{124}Xe . A detection of this decay would provide a new reference for nuclear matrix element calculations. Moreover, if a neutrinoless mode were discovered, it would prove a Majorana nature of neutrinos and would shed light on the effective neutrino mass. The XENON dark matter project, with its dual-phase xenon time projection chambers XENON100 and XENON1T, is well suited for this rare event searches with signatures in the keV-region. The search with the XENON100 detector, containing 29 g of ^{124}Xe , is explained as well as the outlook of its successor XENON1T, which contains 2 kg of the isotope in its active volume.

1. Introduction

For nuclei on the proton-rich side of the mass parabola, where direct β -decay is energetically forbidden, the simultaneous capture of two electrons from the atomic shell

$$(A, Z) + 2e^- \rightarrow (A, Z - 2) + (2\nu_e) \quad (1)$$

is a rare, but possible process. While this mode with emission of two neutrinos ($2\nu\text{2EC}$) is not forbidden by the Standard Model, the possible existence of the neutrinoless double electron capture ($0\nu\text{2EC}$) would be a sign of physics beyond the Standard Model. It would reveal a Majorana nature of neutrinos as well as provide a measure for the effective neutrino mass $m_{\beta\beta}$. The largest uncertainty in the conversion of the half-life of $0\nu\text{2EC}$ to $m_{\beta\beta}$ is introduced by the calculation of nuclear matrix elements. While the matrix elements for the two-neutrino and neutrinoless modes of the double electron capture are not strongly related, they are based on the same nuclear structure models. Therefore, an experimental measurement of the $2\nu\text{2EC}$ half-life would help to test the accuracy of these models.

$2\nu\text{2EC}$ has been observed only in geochemical experiments for ^{130}Ba [1, 2]. Additionally, an indication for $2\nu\text{2EC}$ of ^{78}Kr from a low-background proportional counter exists [3]. In natural xenon, the isotope ^{124}Xe ($Q = 2864 \text{ keV}$ [4]) has an abundance of 0.095% [5] and is predicted to decay via $2\nu\text{2EC}$. As the simultaneous capture of two K-shell electrons is the most likely decay process [6], searches focus on this decay mode. The filling of the vacancies of the daughter atom ^{124}Te leads to the emission of X-rays and Auger electrons with a total energy of approximately 64 keV. There is a wide spread in the predicted half-lives of $2\nu\text{2EC}$ for ^{124}Xe , from $\sim 10^{20} \text{ yr}$ to 10^{24} yr due to differences in nuclear matrix element calculations [7–12]. Previous searches for



$2\nu 2K$, where two K-shell electrons of ^{124}Xe are captured, have been carried out and the current best experimental limit on the half-life, $T_{1/2} > 4.7 \times 10^{21}$ yr (90% confidence level), is set by the XMASS experiment [13], which uses a large-scale liquid xenon detector [13]. Another limit of $T_{1/2} > 1.66 \times 10^{21}$ yr (90% confidence level) was derived from previously published XENON100 data [14]. However, the publicly available data was not well suited for a signal search due to the coarse binning in energy. The limit was calculated from the average background rate for the energy region below ~ 10 keV [15], outside the expected $2\nu 2EC$ signal region and the assumed isotopic abundance of ^{124}Xe did not match the real situation. A study carried out using the 224.6 live days of XENON100 data [16] and additional insight into the experimental details will provide a realistic lower limit on the half-life.

2. The XENON dark matter project

Located at the Laboratori Nazionali del Gran Sasso (LNGS), the XENON100 and XENON1T experiments [17][18] utilize dual-phase xenon time projection chambers (TPC) in order to search for dark matter in the form of Weakly Interacting Massive Particles (WIMPs). While XENON100 was running between 2009 and 2016, the XENON1T experiment started in 2015. The detector principle is based on a cylindrical volume, filled with liquid xenon (LXe) and equipped with radio pure photomultiplier tubes (PMTs) placed in arrays on top and at the bottom. The pressure and temperature conditions ensure a small gaseous phase above the liquid. For XENON100 the TPC is fully surrounded by an active LXe veto viewed by additional PMTs, while XENON1T uses a water tank as an active muon veto. If a particle deposits its energy in the LXe, it creates excited atoms and ions leading to the formation of excimers. The de-excitation of these excimers causes prompt scintillation light ($S1$). In order to avoid recombination of the electrons, which are generated by the ionization process, an electric field (kV/cm) is applied. Consequently, electrons are drifted towards the liquid-gas interface, where a stronger field on the order of 10 kV/cm pushes them into the gas-phase and further accelerates them. This induces a secondary scintillation signal ($S2$) which is proportional to the number of generated electrons ("electroluminescence"). Three-dimensional event vertex reconstruction is achieved by obtaining the interaction depth from the time difference of the two signals and by deriving the (x, y) -position from the hit pattern of the $S2$ signal on the top PMT array. An optimized fiducial volume with a strongly reduced background from external γ -radiation can thus be selected. A detailed description of the detector can be found in Ref. [17].

3. Search for $2\nu 2EC$ with XENON100

In order to search for the $2\nu 2EC$ the data set which consists of 224.6 live days, collected between February 28, 2011 and March 31, 2012, using a fiducial target mass of 34 kg will be analyzed. This data set has already been investigated for different purposes in Refs. [15, 19–22]. As the detector was filled with a mixture of natural xenon and also xenon depleted in ^{124}Xe , the abundance differs from natural xenon with a value of $\eta = (8.40 \pm 0.07) \times 10^{-4}$. Therefore, a total amount of about 29 g of ^{124}Xe is present in the fiducial volume. Since the combination of the $S1$ and $S2$ signals provides a common linear energy scale for both X-rays and Auger electrons at the relevant energies, both signal channels can be used in order to calibrate the energy response. The energy calibration utilizes γ -lines from neutron-activated xenon isotopes between 40 keV and 320 keV. The energy E is then obtained by an linear combination of the $S1$ and $S2$ signals measured in photoelectrons (PE) and the resolution as a function of energy can be modeled using the same γ -lines.

Selection cuts are necessary to ensure data quality and consistency. Due to the short range of the emitted secondary particles (X-rays and Auger electrons) and the relaxation time, only a single energy deposition at 64.33 keV can be observed. Therefore every valid event should have exactly one $S1$ and one corresponding $S2$. In order to avoid dark count contributions at

least two PMTs should contribute to one proper $S1$. Removal of noisy events can be achieved using the information on the signal width ($S1$ and $S2$) and on the signal distribution between the bottom and top PMT arrays. If events have a coincident signal in the veto, it indicates that the event due to multiple scattering induced by external radiation and therefore should not be considered. The acceptance of these selection cuts can be calculated as in Ref. [23] by determining the fraction of events that pass all selection cuts but the one of interest. The knowledge of total acceptance is necessary in order to estimate a half-life for the decay. In order to analyze the prepared data set, a linear background model f_{bkg}

$$f_{\text{bkg}}(E) = a_{\text{bkg}}E + c_{\text{bkg}} \quad (2)$$

where a_{bkg} and c_{bkg} represent the slope and constant term of the background spectrum, can be fitted and compared to a signal model f_{sig} which includes an additional Gaussian signal

$$f_{\text{sig}}(E) = \frac{\Gamma \epsilon \eta m t N_A}{\sqrt{2\pi} \sigma_{\text{sig}} M_{\text{Xe}}} \exp\left(-\frac{(E - \mu_{\text{sig}})^2}{2\sigma_{\text{sig}}^2}\right) + f_{\text{bkg}}(E). \quad (3)$$

Here E is the energy, Γ the decay rate, ϵ the signal acceptance, η the abundance of ^{124}Xe , m the target mass, t measurement time, N_A Avogadro's constant, M_{Xe} the molar mass of xenon, μ_{sig} is the mean energy and σ_{sig} the width of the signal peak. A Bayesian analysis will utilize the *a priori* information on the parameters and uncertainties and provides a measure to compare both scenarios in order to decide whether a signal was detected. Additionally, the classical Feldman-Cousins procedure [24] will be used to cross check the results.

4. Outlook

Due to the lower target mass compared to the XMASS experiment the best sensitivity for $2\nu 2\text{EC}$ is not expected to be reached by the XENON100 experiment. However, the XENON1T experiment [25] will probe a new parameter space, as it is based on the same detector technology but with an increased total target mass of 2 t and is expected to have a reduced background. Additionally, the light yield of XENON1T will be improved and it is also designed to measure signals of high energy more accurately than XENON100. These improvements make it possible to search for neutrinoless double electron capture as well as electron capture with positron emission or double positron decay where the main part of the observable energy is above 1 MeV [26]. Data of XENON1T will be available in 2016.

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References

- [1] Meshik A P, Hohenberg C M, Pravdivtseva O V and Kapusta Y S 2001 *Phys. Rev. C* **64**(3) 035205 URL <http://link.aps.org/doi/10.1103/PhysRevC.64.035205>
- [2] Pujol M, Marty B, Burnard P and Philippot P 2009 *Geochim. Cosmochim. Acta* **73** 6834–6846
- [3] Gavrilyuk Y M, Gangapshev A M, Kazalov V V, Kuzminov V V, Panasenkov S I and Ratkevich S S 2013 *Phys. Rev. C* **87**(3) 035501 URL <http://link.aps.org/doi/10.1103/PhysRevC.87.035501>

- [4] Wang M, Audi G, Wapstra A, Kondev F, MacCormick M, Xu X and Pfeiffer B 2012 *Chin. Phys. C* **36** 1603
URL <http://stacks.iop.org/1674-1137/36/i=12/a=003>
- [5] Berglund M and Wieser M E 2011 *Pure Appl. Chem.* **83** 397–410
- [6] Gavriluk Yu M, Gangapshev A M, Kazalov V V, Kuzminov V V, Panasenko S I, Ratkevich S S, Tekueva D A and Yakimenko S P 2015 Search for $2K(2\nu)$ -capture of ^{124}Xe *2nd International Workshop on Prospects of Particle Physics: Neutrino Physics and Astrophysics* Valday, Russia, February 1-8, 2015
URL <http://inspirehep.net/record/1383174/files/arXiv:1507.04520.pdf>
- [7] Hirsch M, Muto K, Oda T and Klapdor-Kleingrothaus H V 1994 *Z. Phys. A* **347** 151–160
- [8] Aunola M and Suhonen J 1996 *Nucl. Phys. A* **602** 133–166
- [9] Rumyantsev O A and Urin M H 1998 *Phys. Lett. B* **443** 51–57
- [10] Suhonen J 2013 *J. Phys. G* **40** 075102
- [11] Singh S, Chandra R, Rath P K, Raina P K and Hirsch J G 2007 *Eur. Phys. J. A* **33** 375–388
- [12] Shukla A, Raina P K and Rath P K 2007 *J. Phys. G* **33** 549–563
- [13] Abe K *et al.* (XMASS) 2016 *Phys. Lett. B* **759** 64–68
- [14] Mei D M, Marshall I, Wei W Z and Zhang C 2014 *Phys. Rev. C* **89** 014608
- [15] Aprile E *et al.* (XENON100) 2012 *Phys. Rev. Lett.* **109** 181301
- [16] Aprile E *et al.* (XENON100) 2011 *Phys. Rev. D* **83** 082001 [Erratum: *Phys. Rev. D* 85, 029904 (2012)]
- [17] Aprile E *et al.* (XENON100) 2012 *Astropart. Phys.* **35** 573–590
- [18] Aprile E (XENON1T) 2013 *Springer Proc. Phys.* **148** 93–96 (*Preprint* 1206.6288)
- [19] Aprile E *et al.* (XENON100) 2013 *Phys. Rev. Lett.* **111** 021301
- [20] Aprile E *et al.* (XENON100) 2014 *Phys. Rev. D* **90** 062009
- [21] Aprile E *et al.* (XENON Collaboration) 2015 *Phys. Rev. Lett.* **115**(9) 091302 URL <http://link.aps.org/doi/10.1103/PhysRevLett.115.091302>
- [22] Aprile E *et al.* (XENON100) 2015 *Science* **349** 851–854
- [23] Aprile E *et al.* (XENON100) 2014 *Astropart. Phys.* **54** 11–24
- [24] Feldman G J and Cousins R D 1998 *Phys. Rev. D* **57** 3873–3889
- [25] Aprile E *et al.* (XENON) 2016 *JCAP* **1604** 027
- [26] Barros N, Thurn J and Zuber K 2014 *J. Phys. G* **41** 115105